A NEW ANCHORAGE SYSTEM FOR POST-TENSIONING MASONRY WITH CARBON FIBRE REINFORCED PLASTIC (CFRP) TENDONS

Ezzeldin Y. Sayed-Ahmed¹, and Nigel G. Shrive²

1. ABSTRACT

Prestressing of masonry permits the design of more economic and elegant masonry structures. One of the common techniques of prestressing, especially used with masonry, is post-tensioning. The main problem associated with post-tensioning is the corrosion of the steel tendons even when "well-protected". Unbonded exposed steel tendons are particularly susceptible to corrosion. New materials, Fibre Reinforced Plastics (FRP), which are more durable and stronger in tension than steel, can be used to replace traditional steel tendons and thus overcome the corrosion problem. However, a major issue with the introduction of FRP tendons to post-tensioning applications is how to anchor them. A new anchorage system is described here together with the results of direct tension and fatigue tests to verify the anchorage behaviour. The anchorage can be used with bonded or unbonded CFRP tendons in post-tensioning or pre-tensioning applications.

2. INTRODUCTION

Masonry is strong in compression but weak in tension. Thus, the behaviour of masonry structures can be improved by prestressing like those of concrete. Prestressing of masonry has typically been applied in the form of post-tensioning with unbonded steel tendons: the most simple, yet most effective and cheap technique of prestressing masonry walls. One of the most common problems associated with steel tendons is corrosion. Significant loss of prestressing may occur as a result of tendon corrosion which may, in turn, lead to

Key Words: Anchorage System, Cyclic loading, Fibre Reinforced Plastics, Post-tension, Tendons.

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catastrophic failure. Even if failure does not occur, the serviceability advantage of post-tensioned concrete and/or masonry may disappear if the prestressing force in the steel is lost or reduced by corrosion. Thus, post-tensioned masonry elements especially the older ones may require expensive rehabilitation.

The idea of replacing steel tendons with Fibre-Reinforced-Plastic (FRP) tendons has emerged. FRP tendons have higher durability, corrosion resistance, tensile strength and lighter weight than traditional steel tendons. Most FRP's used today are reinforced with glass (GFRP), aramid (AFRP), and/or carbon (CFRP). Of the different FRP currently available, CFRP exhibits the highest tensile strength (Hercules aerospace\(^1\)), excellent fatigue strength (Rostasy et. al.\(^2\)) and very low relaxation (Rao\(^3\) and Santoh\(^4\)). In Table 1, most of known mechanical properties of CFRP are shown.

The table shows that CFRP exhibits very high short-term static tensile strength, with a high modulus of elasticity. When subjected to $2 \times 10^6$ cycles of loading, the Leadline (CFRP tendon produced by Mitsubishi Chemical Corporation) tendon has an endurance limit of 1100 MPa and CFCC (CFRP tendon produced by Tokyo Rope Manufacturing Co., Ltd.) 1300 MPa. Stress ratios of 0.54 and 0.1 were used for the CFCC and Leadline respectively (Tokyo Rope\(^5\) and Yagi and Hoshijima\(^6\)). This shows that CFRPs also exhibit good dynamic tensile strength. In other tests performed by Yagi and Hoshijima\(^6\), Leadline showed a loss of about only 0.5% of the strength after 528 hours in alkali solution at 40°C. Tokyo Rope reported that CFCC strands in pH 13 alkali solution at 60°C retained 97.6% of their strength after 2500 hours. These results show the high durability of CFRP tendons.

CFRP tendons also have some disadvantages. Typically, they do not exhibit an inelastic response like steel tendons: no ductility is observed and failure strains are relatively low (about 1.5%). This shortcoming must be addressed in design procedures before there can be widespread practical usage of FRP in prestressing applications. The second shortcoming of CFRP tendons is the relatively high price compared to even well protected steel strands. CFRP costs can be 1.7 to 3.0 times the cost of the steel strands. However, the cost of handling and transportation is a plus for CFRP as they are much lighter than steel. When comparing CFRP with steel, the price/performance of the tendon should be considered rather than the price alone which yields an advantage for CFRP tendons. The price of CFRP has been going down over the past few years, so the cost disadvantage may disappear in time.

Other than these disadvantages, the key problem facing the application of CFRP tendons in post tensioning is how to anchor them. The traditional anchorages for CFRP tendons involve two main types:

1. Bond anchorages where epoxy resin or expansive cement were used. These anchorages were developed mainly for pre-tensioning applications. Loss of load due to displacements and expected large creep in the resin/cement based anchorage systems is likely to make them inadequate for “short” span post-tensioned members such as masonry walls.

2. Mechanical anchorages like the traditional wedge anchorage systems. Wedge systems affect the load capacity of the FRP as they tend to dig into the surface of the tendon causing premature failure. In the case of using the die-cast wedge system (used by Tokyo Rope for CFCC tendons) the main disadvantage arises from having to redefine the length of the tendon.
Table 1. Mechanical properties of CFRP tendons. (Tokyo Rope 5, Mitsubishi 7, Daniel et al. 8, Nanni et al. 9, Holte et al. 10, and Sayed-Ahmed and Shrive 11).

<table>
<thead>
<tr>
<th>Property</th>
<th>CFRP</th>
<th>Leadline</th>
<th>CFCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre/resin</td>
<td>CFRP</td>
<td>Carbon/ Epoxy</td>
<td>Carbon/ Epoxy</td>
</tr>
<tr>
<td>Anchorage System</td>
<td>Wedge/ soft metal</td>
<td>Resin anchor</td>
<td></td>
</tr>
<tr>
<td>Minimum fibre volume ratio</td>
<td>0.65</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.53</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Longitudinal tensile strength (GPa)</td>
<td>2.25~2.55</td>
<td>1.8~2.1</td>
<td></td>
</tr>
<tr>
<td>Transverse tensile strength (MPa)</td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal modulus (GPa)</td>
<td>142~150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse modulus (GPa)</td>
<td>10.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-plane shear strength (MPa)</td>
<td>71</td>
<td></td>
<td></td>
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<tr>
<td>In-plane shear modulus (GPa)</td>
<td>7.2</td>
<td></td>
<td></td>
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<tr>
<td>Major Poisson’s ratio</td>
<td>0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor Poisson’s ratio</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bond Strength (MPa)</td>
<td>9.7~13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. longitudinal strain (%)</td>
<td>1.3~1.5</td>
<td>1.57</td>
<td></td>
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<tr>
<td>Max. transverse strain (%)</td>
<td>0.6</td>
<td></td>
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</tr>
<tr>
<td>Long. comp. strength (MPa)</td>
<td>1440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trans. comp. strength (MPa)</td>
<td>228</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long. thermal exp. coef. (°C)</td>
<td>-0.9x10^-6</td>
<td>0.5x10^-6</td>
<td></td>
</tr>
<tr>
<td>Trans. thermal exp. coef. (°C)</td>
<td>27x10^-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relaxation ratio (%) at room</td>
<td>2-3%</td>
<td>1%</td>
<td></td>
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<tr>
<td>temperature.</td>
<td></td>
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Hence, the first requirement for the introduction of post tensioning with CFRP tendons to the construction industry is the development of an appropriate anchorage system which can be used on site, is durable and minimizes prestress loss.

3. MAIN REQUIREMENTS FOR P/T ANCHORAGE SYSTEMS

The main requirements for such a post-tensioning anchorage are:
1. The anchorage system must develop a minimum of 95% of the nominal ultimate tensile strength of the tendon. This is the minimum "anchorage efficiency". The tendon should thus fail at load above 95% of its nominal tensile strength rather than slip out of the anchorage, fail prematurely or cause anchorage failure.

2. At the release of the jacking force, the anchorage must undergo a small, predictable displacement to reduce the amount of prestressing loss in the tendons.

3. Long-term static stress (prestress) should not reduce the tensile strength of the tendon significantly. This means that the tendon/anchorage assembly should have adequate creep rupture strength over the service life of the structure. Furthermore, the stressing operation should only have to be performed once. Thus, creep in the anchorage must be minimal.

4. The dynamic stress amplitude of the service load state should not reduce the efficiency of the anchorage/tendon assembly. In other words, fatigue failure of the anchorage components should not occur, nor should the anchorage induce failure of the tendon.

5. Environmental effects must not affect or reduce the strength of the tendon/anchorage assembly significantly.

6. Galvanic or other corrosion reactions between the tendon and the anchorage or between the anchorage and the surrounding media (if embedded) must be avoided.

Many anchorage systems have been developed for post-tensioning with FRP's which satisfy some, but not all of the above requirements (Holte, Shrive et al., Harada et al., and Khin et al.). The most common failure modes of FRP anchorage systems are:

1. Rupture of the cable/rod within its free length. This is the ideal mode which indicates that the anchorage is working well because the tensile capacity of the FRP cable/rod is developed totally.

2. Shear failure in the anchorage zone. The cable/rod may be pinched due to the large shear stress concentration that occurs with certain anchorage geometries. The shear stress causes premature failure of the tendon. For example, this kind of failure occurs if the anchorage systems currently used for steel tendons are used with CFRP tendons.

3. Bond failure between the epoxy and the tendon. In many epoxy resin anchorage systems developed for FRP's, the bond between the resin and the tendon fails. There is no subsequent load transfer between the anchorage and the tendon.

4. Excessive deflection and/or long-term creep. The low elastic modulus epoxy resin is very sensitive to high temperature and also exhibits long term creep deformation. As a result, undesired longitudinal deformation resulting from these two factors may lead to significant loss of prestress force. This serviceability type of failure occurs with epoxy resin anchorage systems.

5. Slip failure between the tendon and the grip. This type of failure is catastrophic and leads to complete loss of the prestressing force.

There is a need for a new anchorage system which meets all the required technical criteria, is simple to use and which can be utilized in post-tensioning applications. The latter requirement adds further criteria regarding durability and long term behaviour.

4.0 THE NEW ANCHORAGE SYSTEM

4.1 Description of the New Anchorage System

The new anchorage is resin-free and requires no new or advanced technology either to
manufacture or use. It is subject to patent examination. The single strand anchor is made of three parts:

1. An outer steel cylinder (outer barrel) with a conical hole as shown in Figure 1. The inside surface of the hole is very smooth and grease is added to facilitate movement between this barrel and the inner wedge.

2. A four-piece wedge (spike) which has a smooth outer surface. The wedge has a central hole and the surface of this hole is sand-blasted. The edges of the four pieces at this hole are rounded to reduce the stress concentration on the tendon when the spike is seated in barrel. The angle of inclination of the outer surface of the spike is slightly larger than that of the inner surface of the barrel. The inner hole of the spike is drilled to the outer diameter of the inner sleeve.

3. The inner sleeve is made out of steel or copper and has a small wall thickness. The inner diameter of the sleeve is drilled to the diameter of the tendon. The outer surface of the sleeve is sand-blasted.

Early prototypes were made of mild steel to larger dimensions. Test results and numerical analyses using the finite element method allowed us to reduce the dimensions to make the anchorage more practical. The barrel and wedges of this latter anchorage are made of high strength stainless steel (0.2% proof stress of 862 MPa and tensile strength of 1000 MPa) with the inner sleeve made of soft copper. It is possible that materials other than stainless steel and copper could be used for the anchorage, and variations on the theme here could be used to make multi-strand anchorages.

4.2 Testing the New Anchorage System

Two types of test were performed on the CFRP tendons with the new anchorage system. The first was a direct tensile test to obtain the efficiency of the anchorage and the static short-term tensile strength of the tendon anchorage assembly. The second was a fatigue test to check one aspect of the long term behaviour and the dynamic axial strength of the tendon/anchorage assembly when subject to dynamic cyclic loading.

4.2.1 Short-term axial strength (direct tension test)

Tension tests with the anchorage was performed using 8 mm diameter indented spiral Leadline tendon in a standard tensile testing machine. All the CFRP specimens used in the tests were about one metre in length. Twenty four tests were performed.

The maximum tensile strength of 8 mm Leadline as defined by the manufacturer is 104 kN which was taken to be the nominal failure load of the tendon. To achieve 95% efficiency in the anchorage, a failure load of 99.0 kN is required. Modifications after initial failure loads of 104 kN gave an average failure load of 114 kN (range: 105 - 124 kN), exceeding the specified nominal strength of the tendon, guaranteed by the manufacturer, by 10%. Failure occurred in the free length of the Leadline away from the anchorage zone despite the fact that some cracks tend to extend to (and may be initiated at) the anchorage zone. Failure typically started with the splintering of a small amount of fibres at more than 99% of the failure load. Catastrophic failure followed very quickly with the remainder of the test specimen shattering apart. In fact, failure of the CFRP tendon was very sudden. When failure was filmed using 60 frame/second video-camera, in one frame a dark cloud appeared around the free length of the CFRP tendon and in the very next
Figure 1. Components and dimensions of the new patent anchorage system

frame the tendon had shattered leaving pieces of cracked tendon in the anchorage and around the test machine.

At failure, with the preliminary tests using the prototype model, the maximum seating of the anchorage was about 5 mm from our lightly placed initial assembly position. When the anchorage system was stressed up to 70 kN, seating the order of 3 mm was observed.
This load would be appropriate for practical post-tensioning with the 8 mm diameter tendon. This 3 mm displacement was eliminated in the subsequent tests by seating the anchorage with an oil pump and jacking frame before use.

4.2.2 Dynamic strength (fatigue testing)

The fatigue life of any material usually depends on the maximum stress, stress range, stress ratio, rate of loading/unloading, specimen geometry, grips, temperature, humidity, ... etc. Thus, the evaluation of the fatigue behaviour usually requires a large number of tests. We have begun to evaluate the behaviour of the tendon/anchorage assemblage subject to cyclic loading. The specimens used were 8 mm diameter Leadline (CFRP) tendons approximately one metre long. Five tests were performed as follows:

1. A total of $1.7 \times 10^6$ cycles (at a rate of 5 cycles/s) with the following sequential load ranges and number of cycles:
   - 30 - 50 kN (29% - 48% of the nominal strength) for 800,000 cycles.
   - 40 - 60 kN (38% - 58% of the nominal strength) for 500,000 cycles.
   - 50 - 70 kN (48% - 67% of the nominal strength) for 330,000 cycles.
   - 60 - 80 kN (57% - 77% of the nominal strength) for 72,700 cycles before failure took place at this load level.

2. A total of $2.0 \times 10^6$ cycles with the following sequential load ranges and number of cycles:
   - 40 - 60 kN (38% - 57% of the nominal strength) at 5 cycles/s for 1,995,000 cycles.
   - 6 - 60 kN (5% to 57% of the nominal strength) at 2 cycles/s for 5,200 cycles, before failure at this load level.

3. A total of $0.5 \times 10^6$ cycles with the following sequential load ranges and number of cycles. This test follows the PTI recommended test for steel tendon/anchorage assemblies:
   - 62 - 68 kN (60% to 66% of the nominal strength) at 5 cycles/s for 500,000 cycles.
   - 52 - 83 kN (50% to 80% of the nominal strength) at 1 cycle/s for 50 cycles.
   - A static tension test up to 99 kN (corresponding to 95.2% efficiency) with no failure.
   - At this stage the PTI test had been completed successfully so we loaded the specimen between 5 kN and 55 kN at 10 cycles/s. When the first crack appeared at about 8000 cycles, we stopped the dynamic loading and loaded the specimen statically. The tendon carried 70 kN before failure.

4. A total of $2.25 \times 10^6$ cycles with the following sequential load ranges and number of cycles:
   - A static load up to 95 kN then unloading the specimen.
   - 62 - 68 kN (60% to 66% of the nominal strength) at 5 cycles/s for 500,000 cycles.
   - 52 - 83 kN (50% to 80% of the nominal strength) at 1 cycle/s for 50 cycles.
   - A static tension test up to 95 kN with no failure then unloading the specimen.
   - 1,750,000 cycles between 45 kN and 55 kN at 5 cycles/s.
   - Loading between 40 kN and 60 kN at 5 cycles/s. When the first crack appeared at about 5500 cycles, we stopped the dynamic loading and loaded the specimen statically. The tendon carried 75 kN before failure.

5. A total of $2.42 \times 10^6$ cycles with the following sequential load ranges and number of cycles:
   - Three static loading and unloading cycles up to 40, 60 and 90 kN at a rate of 1 kN/s.
   - 62 - 68 kN (60% to 66% of the nominal strength) at 5 cycles/s for 721,000 cycles.
   - 52 - 83 kN (50% to 80% of the nominal strength) at 1 cycle/s for 50 cycles.
   - A static tension test up to 95 kN at a rate of 1 kN/s with no failure.
• Failure occurred after 1,700,000 cycles between 45 kN and 55 kN at 10 cycles/s.

The previous preliminary cyclic loading tests performed on the CFRPs tendon/anchorage assembly showed that rate of loading is less significant than the stress range. Four rates of loading (1, 2, 5 and 10 cycles/s) were used and none of them had a significant effect of the fatigue strength of the tendon. On the other hand, the stress range appeared to have a significant effect on the fatigue strength of the CFRP tendons. With a narrow stress range, the maximum strength could have been increased up to 80 kN, but as the stress range was increased the maximum strength which corresponds to the fatigue strength decreased. Despite the fact that more tests are required to prove this conclusion, these preliminary results are in contrast with the specifications prepared by Tokyo Rope$^5$ and Santoh$^4$ for the CFCC tendons where the mean stress is considered as the governing (effective) factor against fatigue. Our results however tend to agree with those of Yagi et al.$^6$ for Leadline.

4.2.3 Analysis of cyclic loading test 5 results

In the cyclic loading test number ‘5’, two sets of strain gauges were mounted the free length of the specimen to collect data during the test: one on the smooth surface of the Leadline specimen (strain gauge 1) and the other on the indented surface (strain gauge 2). During static loading, we took 1 reading/s corresponding to 1 reading/kN. During the cyclic loading we took 30 reading/s corresponding to 6 readings/cycle and 3 readings/cycle for the 5 cycle/s and 10 cycle/s loading rates respectively. Data were collected about every 200,000 cycles. Some of these data are shown in Figures 2 and 3. In the Figures, the cross-head deformation (stroke in mm) and the strain gauge readings are plotted against the load corresponding to static loading and unloading of the specimen to 40 kN and 90 kN. Readings from strain gauge 1, mounted on the smooth surface of the
Figure 3. Results of test 5 - load up to 90 kN.

Leadline, result in elastic moduli of 140 GPa, and 148 GPa. After applying cyclic loading the elastic modulus obtained was 150 GPa which indicates that there may be a marginal effect of cyclic loading on the stiffness of the tendon/anchorage assembly. The corresponding values from strain gauge 2 (mounted on the indent) are 158 GPa, 166 GPa and 167 GPa which is 11% to 18% higher than the value of elastic modulus of 142 GPa given by the manufacturer (Mitsubishi, and Daniel and Ishai).

The permanent increase in stroke of 2.5 mm after unloading is due to seating of the wedges of each anchorage by about 1.25 mm each. It is interesting to note that the seating started at about 70 kN. The load used to seat the wedges before testing was about 65-70 kN which is why higher loads may have induced the further seating during testing. However in practice, the tendon will not usually be prestressed beyond about 70% of its ultimate capacity (73 kN for the 8 mm Leadline used here) and thus, the amount of seating due to loading will be negligible.

5. CONCLUSIONS

A new anchorage system for CFRP tendons has been developed and tested to yield the required efficiency for post-tensioning applications, and to provide fatigue resistance meeting the PTI requirements (adopted from steel strands).

6. ACKNOWLEDGMENT

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